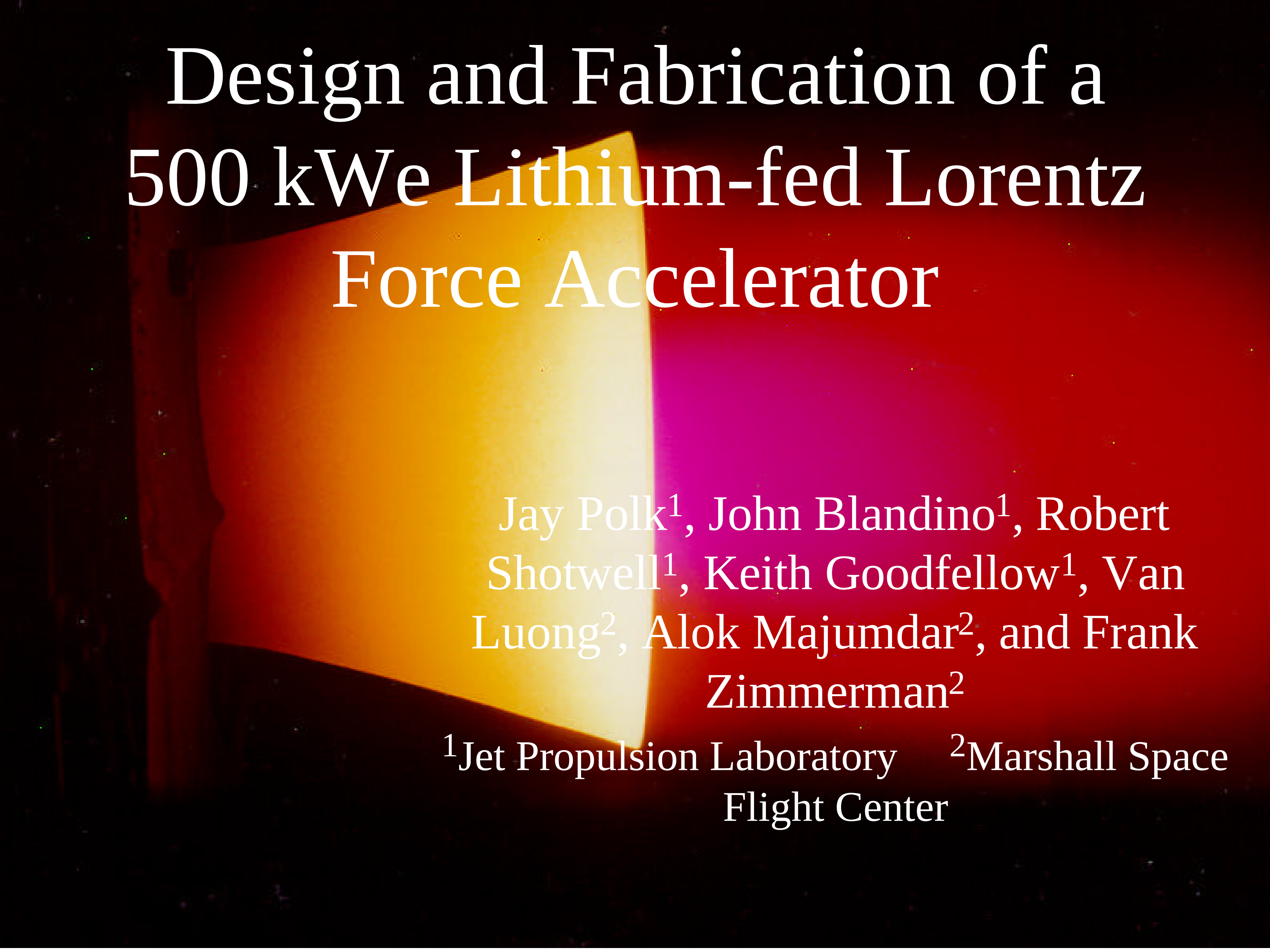
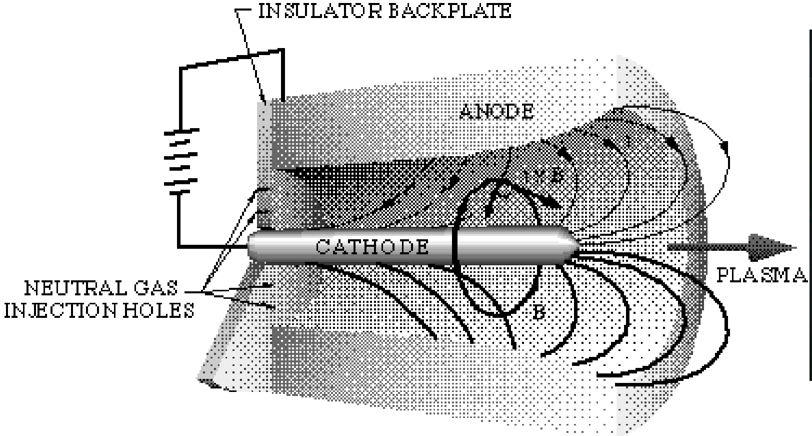


Design and Fabrication of a 500 kWe Lithium-fed Lorentz Force Accelerator

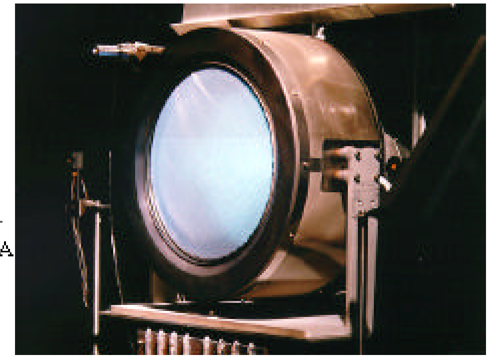
Jay Polk[1], John Blandino[1], Robert Shotwell[1], Keith Goodfellow[1], Van Luong[2], Alok Majumdar[2], and Frank Zimmerman[2]

[1]Jet Propulsion Laboratory [2]Marshall Space Flight Center

Lithium Lorentz Force Accelerators are Ideal for Very High Power Applications



J X B forces accelerate plasma axially and radially



2.3 kWe NSTAR Ion Thruster

200 kWe MAI Li- LFA

Electromagnetic acceleration allows >200 times the power of the NSTAR ion engine to be processed in the same volume

Lithium-fed Lorentz Force Accelerators (LFA's) are under investigation because:

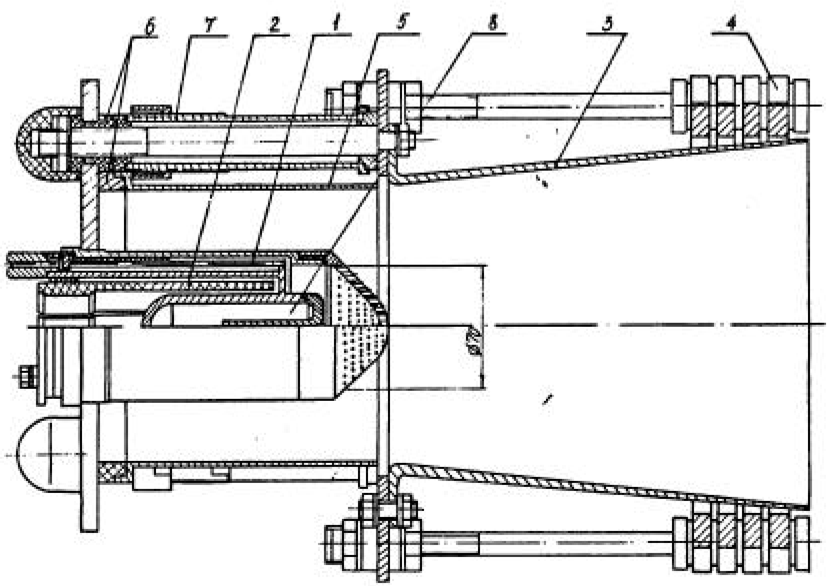
- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency--low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

Very high power propulsion systems enable many far-term missions:

- Orbit-raising heavy payloads in Earth orbit
- Piloted Mars and Mars cargo missions
- Fast robotic and piloted outer planet missions
- Interstellar precursor missions

Large Russian Experience Base Demonstrates Technology Potential for HEDS

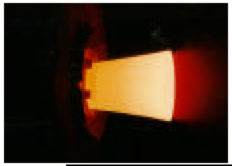
Organization	Power (kWe)	Current (kA)	Specific Impulse (s)	Efficiency	Typical Operating Period	Notes
NIITP	300-1000	6-15	3500-5000	40-60	5 min	NIITP design
Fakel	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	300-500	6-9	3500-4500	40-60	30 min	Energiya design
Energiya	500	9	4500	55	500 hours	Endurance test of Energiya design
Energiya	250-500	5-8	3000-4500	35-55	30-60 min	Coaxial thruster with long cathode. Stopped because of cathode failure
MAI	300-500	6-9	3500-4500	40-60	30 min	Energiya design



Energiya 500 kWe thruster design.

- Development of high power Li-fed thrusters continued in Russia.
- Capabilities required for HEDS largely attained.
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed. Several thousand hour life projected.

Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

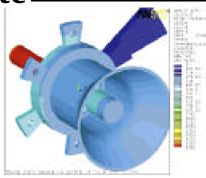


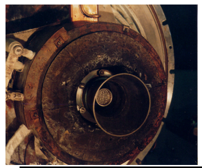
POWER

200 kWe Steady State

• Anode Texturing
• Heat Pipes

1 - 5 MWe Steady State





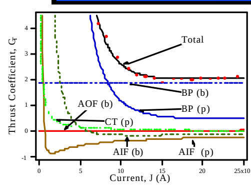
MULTIMEGAWATT TECHNOLOGY

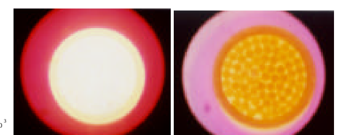
PERFORMANCE

η = 50%
Isp = 4000 s

• Lithium Propellant
• Active Turbulence Suppression

η = 60%
Isp 8000 s



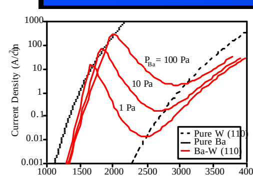


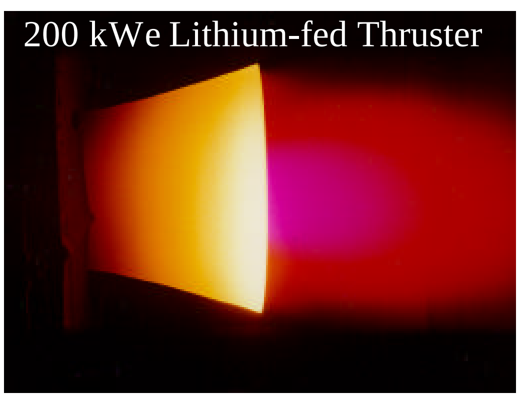
LIFETIME

100's of Hrs At 3000 A

• Multi-Channel Hollow Cathodes
• Barium Addition

10000 Hrs At 20000 A



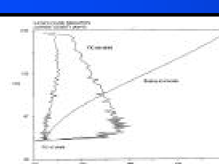


PLUME CONTAMINATION

10^{-8} g/cm^{2}s at 0.3 m

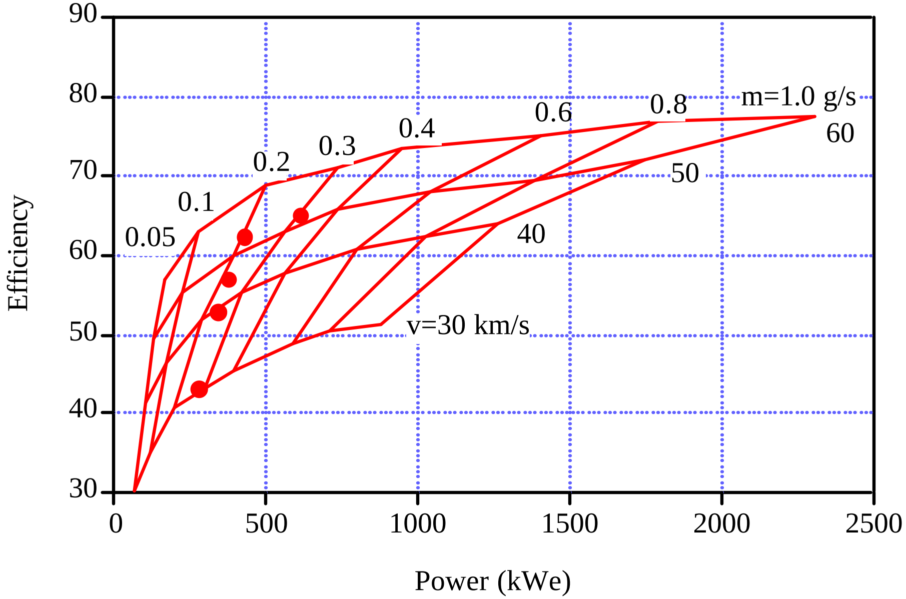
• Plume Shields
• Booms

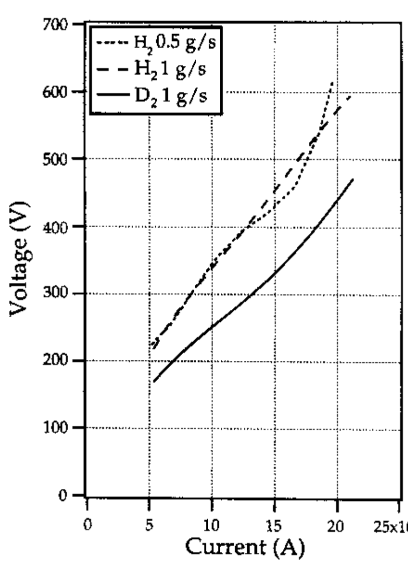
10^{-10} g/cm^{2}s at 30 m

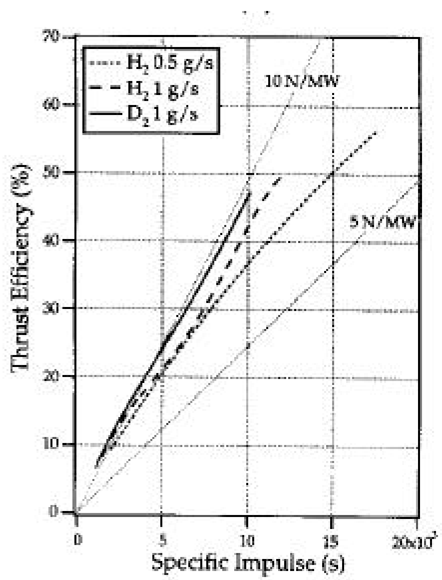


STATE OF THE ART

Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path







- **0.5 -- 1 MWe lithium-fed thrusters are ideal for near-term applications**
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Orbit transfer and Mars cargo applications
- **1-- 5 MWe lithium thrusters fulfill mid-term propulsion requirements**
  - Second generation power systems at 10--30 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions
- **5--10 MWe hydrogen or deuterium-fed thrusters open up the solar system**
  - Third generation (very low alpha) power systems at 100's of MWe's
  - Terminal voltage with lithium is too low to process very high power levels; hydrogen appears to provide required efficiency at Isp's of 10000-15000 s
  - Piloted missions to Mars and the outer planets

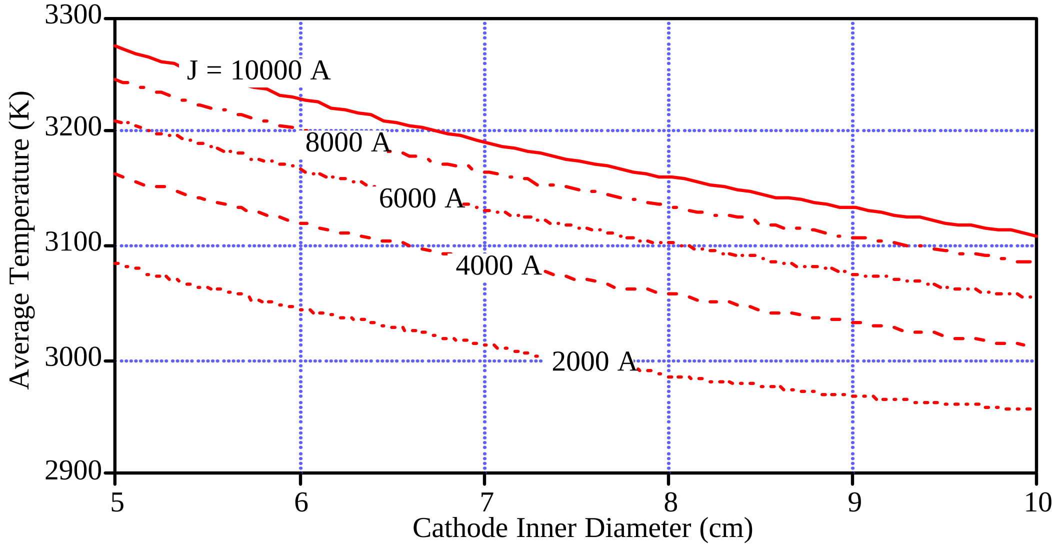
Overview of the 500KW Design

- Chart not available

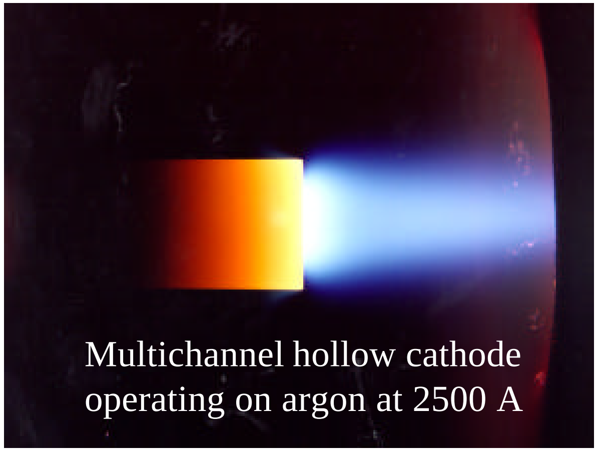
Performance Requirements Dictate Some Design Characteristics

- Chart not available

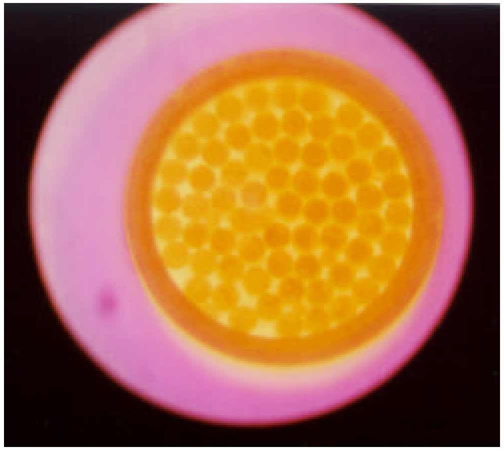
Cathode Design Exploits Multihollow Cathode Geometry

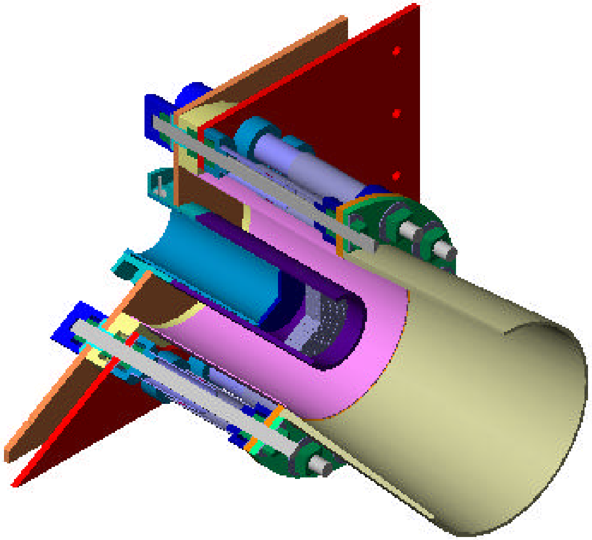


- Total cathode emission current dictated by power requirements
- Cathode sized to give tolerable current density assuming thermionic emission from pure tungsten surfaces in multichannel hollow cathode
- Cathode tube fabricated by vacuum plasma spray deposition by MSFC; rods fabricated from 6.4 mm diameter tungsten welding rod

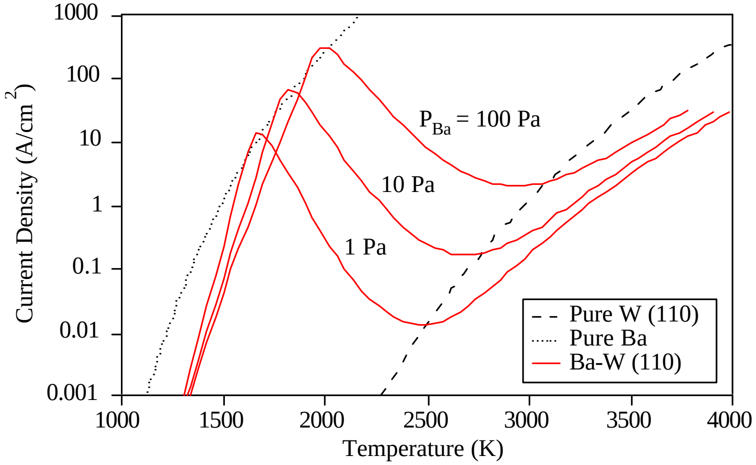


Multichannel hollow cathode operating on argon at 2500 A



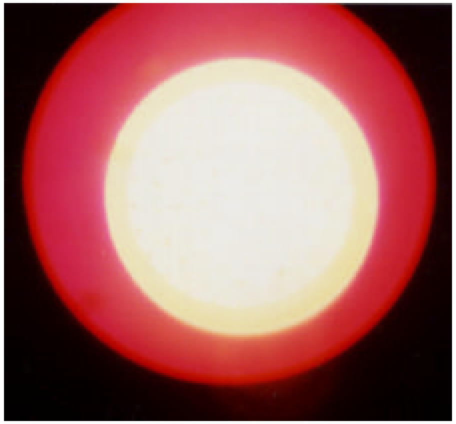


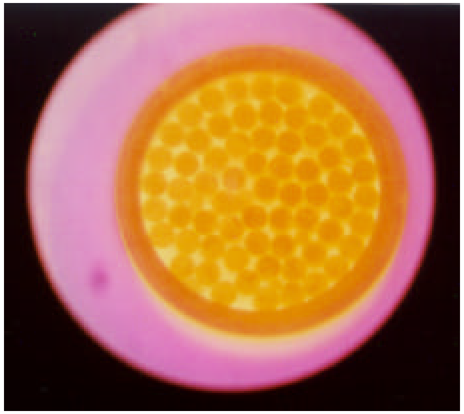
Achieving Long Cathode Life Will Likely Require Addition of a Small Amount of Barium to Propellant



Higher current density capability enabled by addition of barium vapor to propellant flow through cathode

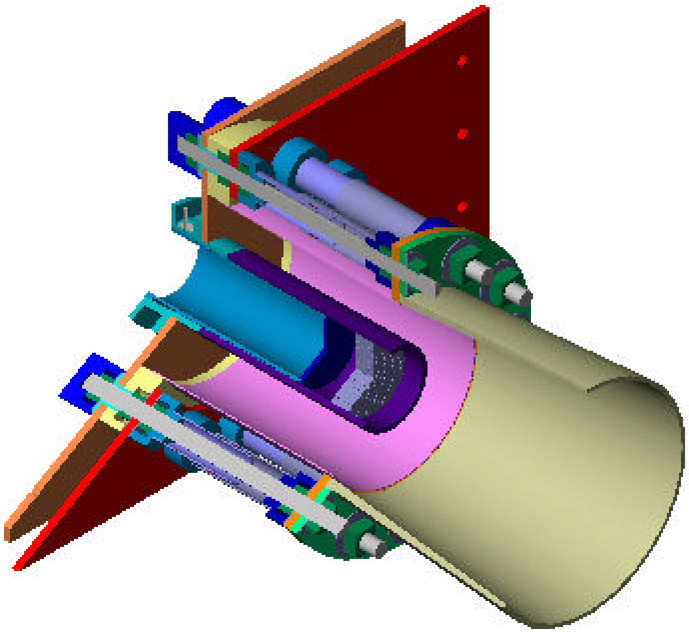
Preliminary experiments at MAI show 300-400 °C decrease in cathode temperature with barium addition

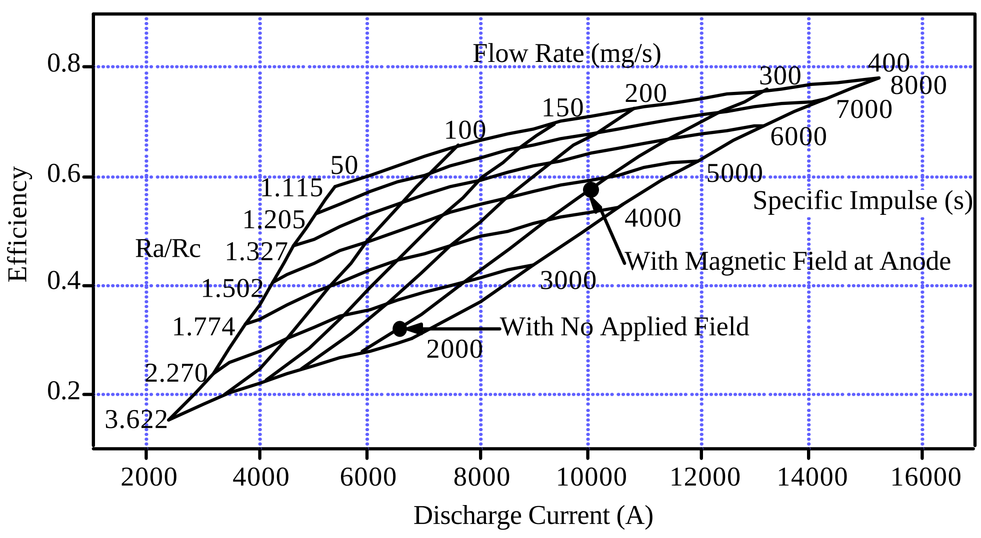




- Work function of pure tungsten is relatively high; resulting operating temperature will limit cathode lifetime to several hundred hours
- JPL models of surface kinetics suggest that modest amounts of barium in propellant stream reduce the work function and lower cathode temperatures
- Preliminary experiments at MAI verify temperature decrease
  - Up to 300-400 °C drop in temperature observed in tests with uncontrolled flows of Ba
  - Very high barium flow rates actually limit achievable discharge current
- 500 kWe engine cathode assembly is designed to accommodate a separate barium vaporizer

Anode Design is Driven by Thermal and Performance Considerations



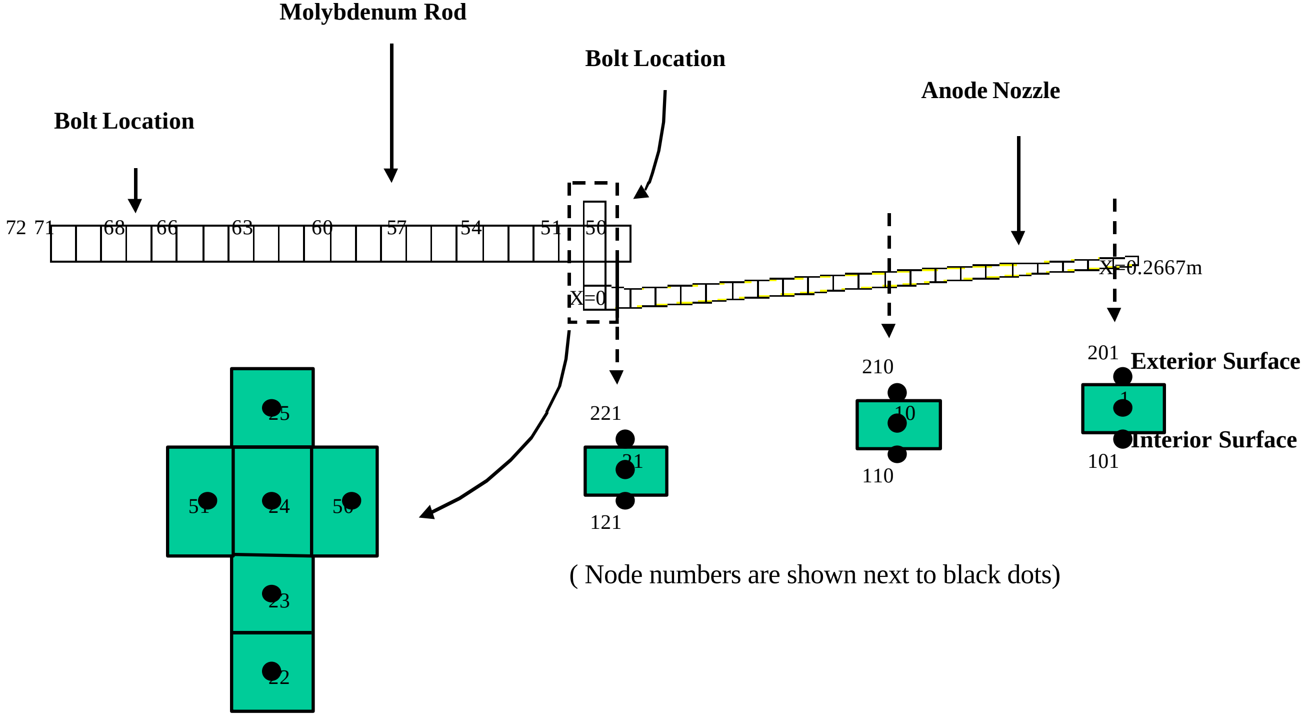


- **The radiation-cooled anode design is a compromise between thermal management and performance**
  - Isp requirement drives design to as small an anode radius as possible
  - Radiative cooling requirement favors large anode areas
  - Minimizing temperature difference between interior and exterior anode surfaces drives design to thin anodes
  - Anode must have sufficient cross-sectional area to prevent excessive Joule heating
- **Anode dimensions were chosen on the basis of**
  - Approximate performance analysis
  - Anode thermal analysis
  - Fabrication constraints

Anode Thermal Analysis of Candidate Design Incorporates All Important Heat Transfer Processes

Marshall Space Flight Center
Thermodynamics and Heat Transfer Group

- 2-D axisymmetric geometry
- Temperature dependent thermal conductivity, resistivity and emissivity
- Arc heat inputs on interior surface, volumetric Joule heating, heat conduction along anode support rods
- Radiative coupling between anode, cathode, discharge chamber and environment determined from radiative view factors



(Node numbers are shown next to black dots)

Results Indicate Tolerable Temperatures with High Emissivity Coatings

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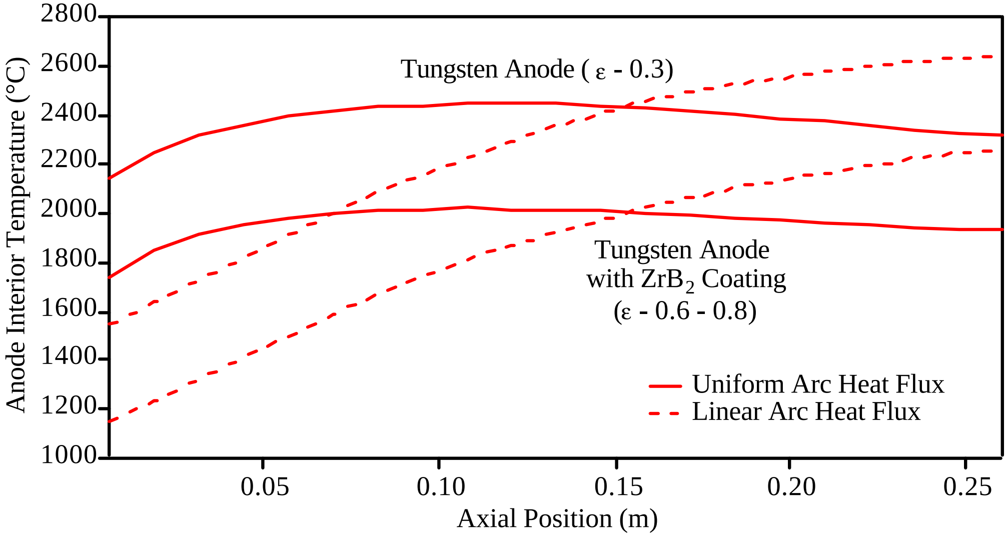
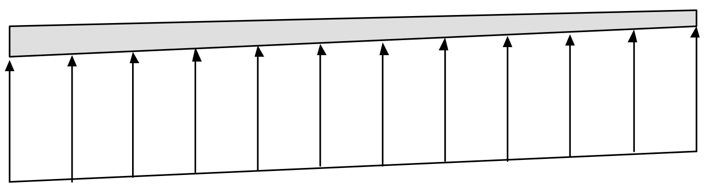
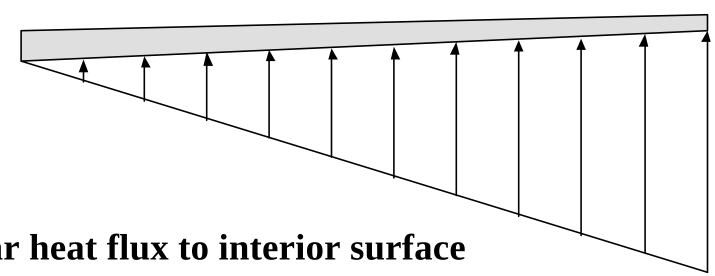




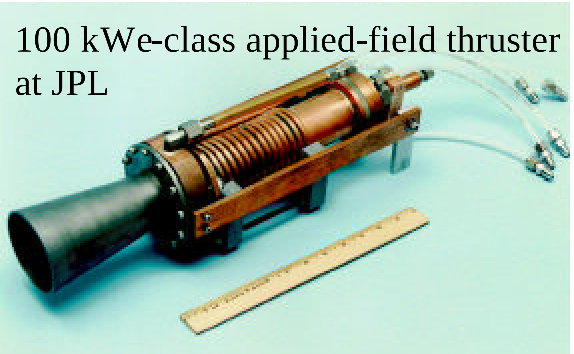
Uniform heat flux to anode interior surface



Linear heat flux to interior surface

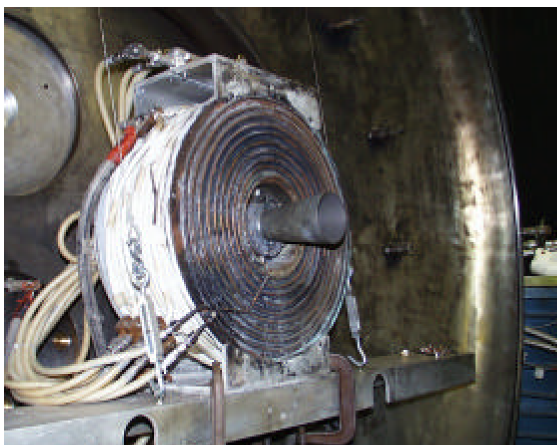
- 200 kW total arc heat load assumed as realistic upper bound for 500 kWe operation
- Anode heat flux distribution is not known; two distributions modeled to determine sensitivity
- Emissivity of anode exterior surface treated parametrically to study effect of high emissivity coatings
- Peak temperatures with ZrB_2 plasma-sprayed coatings developed in JPL 30 kWe ammonia arcjet program are 2000-2200 °C

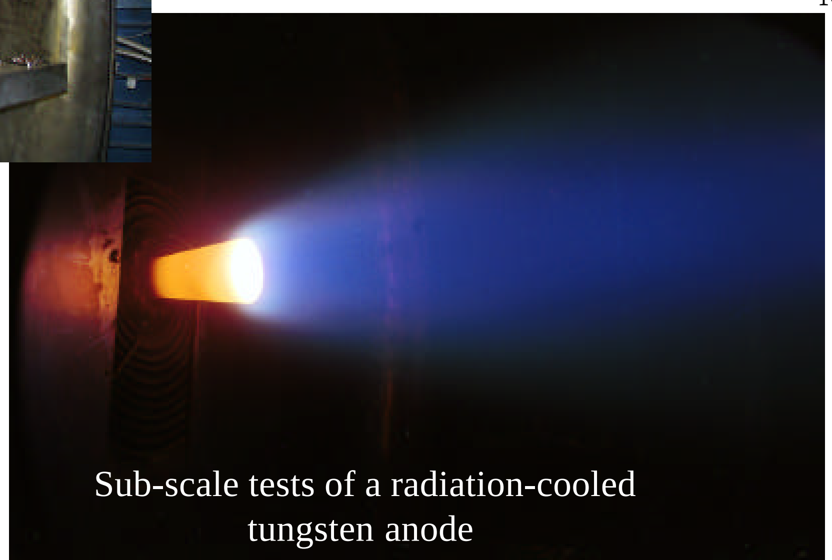
Subscale Tests Used to Validate Anode Fabrication Methods



100 kWe-class applied-field thruster at JPL

- Several methods for fabricating large, thin-walled tungsten structures evaluated
  - Conventional machining
  - Chemical vapor deposition
  - Vacuum plasma spray deposition
- Subscale tests with applied field MPD thruster operated with argon at power level up to 50 kWe demonstrated plasma sprayed anode operation with temperatures as high as 2100 °C
- Test anodes fabricated at MSFC demonstrated feasibility of fabricating large scale parts; actual anodes now being sprayed

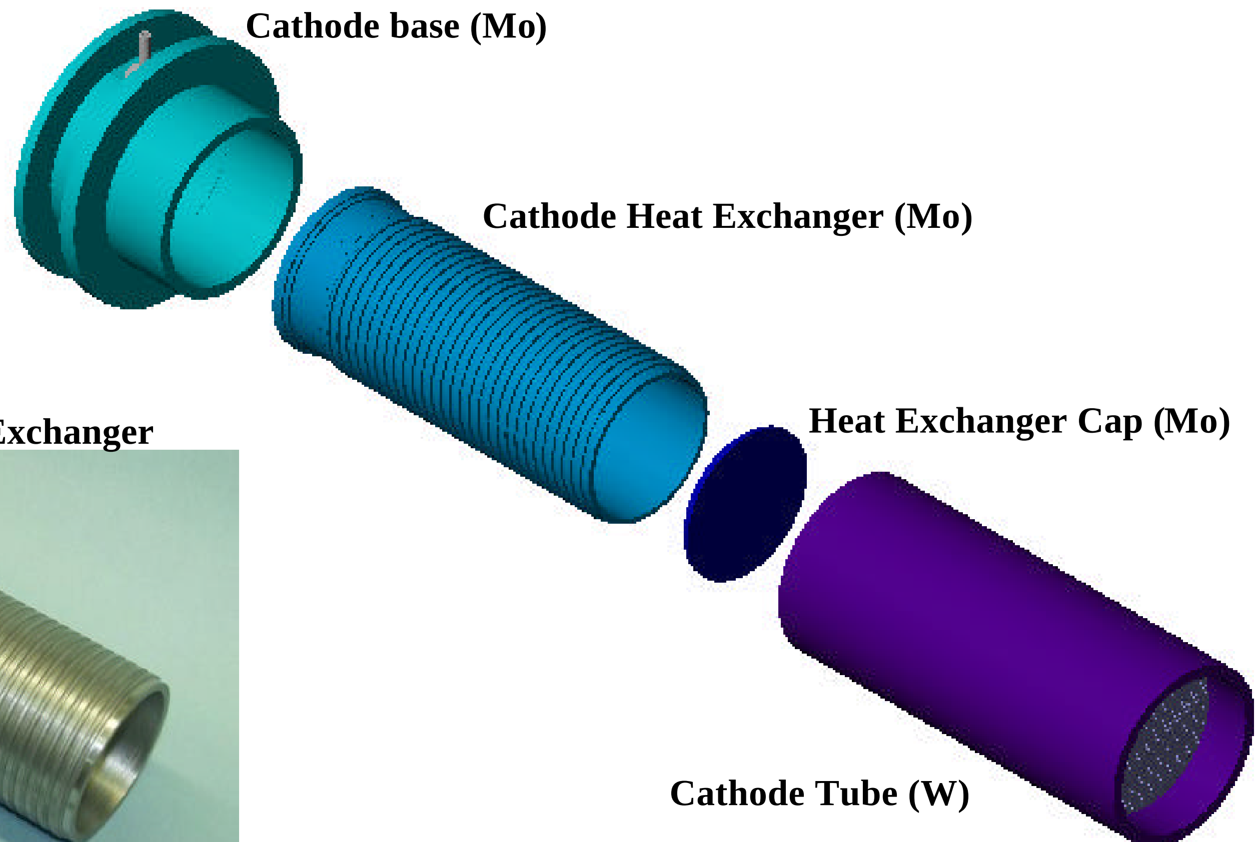




Sub-scale tests of a radiation-cooled tungsten anode

Full scale test anode fabricated at MSFC/Rocketdyne Vacuum Plasma Spray Facility

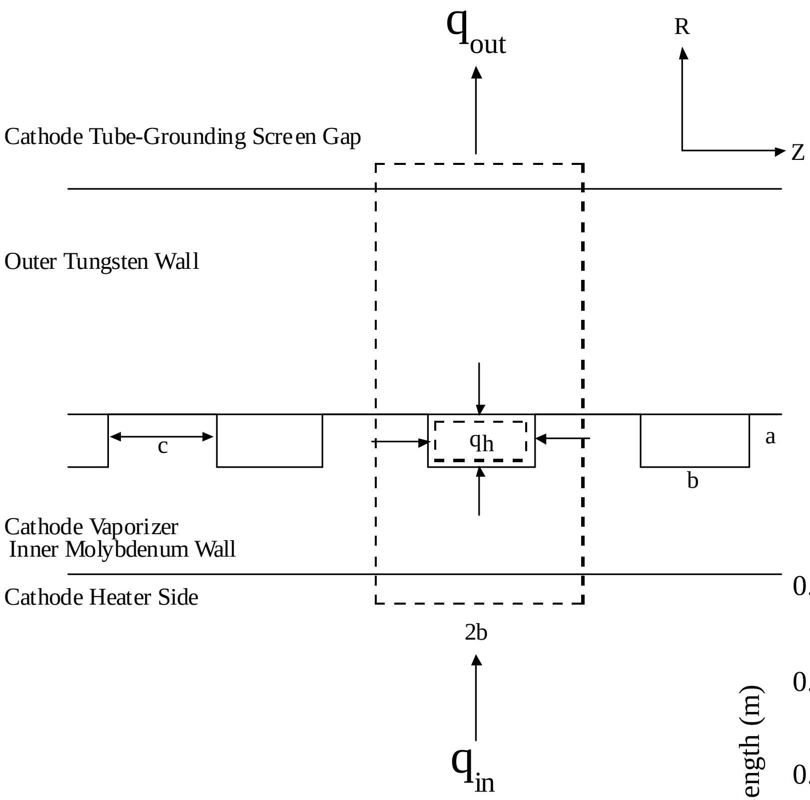
Lithium Vaporizer is Integrated Into Engine Cathode Assembly



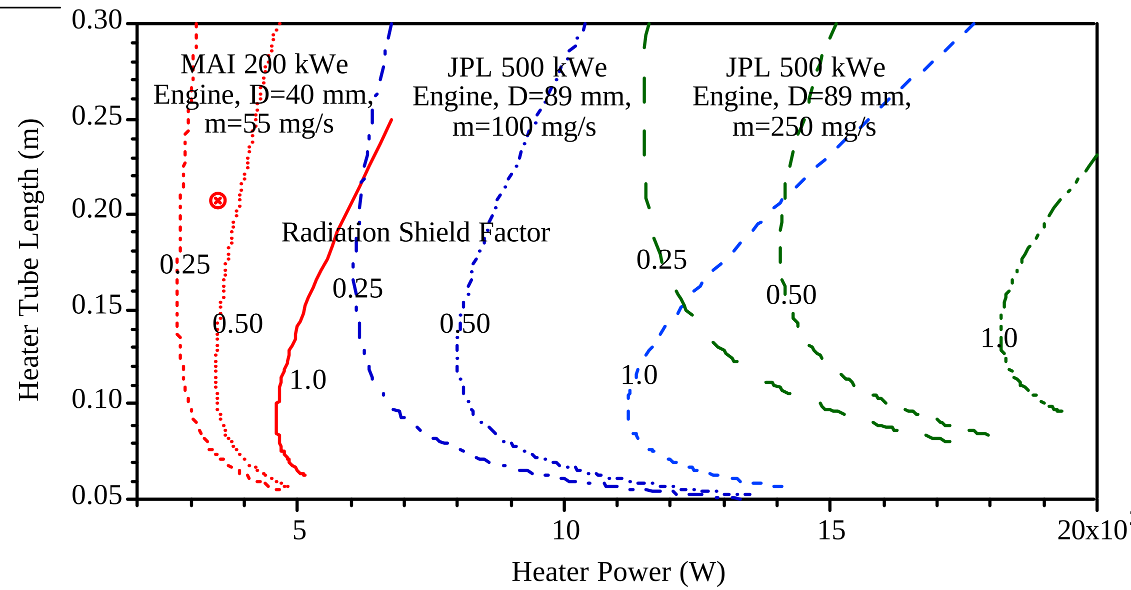
Actual Molybdenum Heat Exchanger

Lithium Vaporizer Heat Exchanger Sized by Approximate Thermal Analysis

Vaporizer Heat Exchanger Geometry



- Vaporizer length required to vaporize lithium is determined by heat input from internal heater, lithium flow rate and heat loss by radiation from exterior surface
- Model validated by comparison with data from MAI 200 kWe engine
- Results suggest 15 kW heater is sufficient for startup; heat conduction from cathode reduces heater requirements during operation



The High Power Lithium Plasma Thruster Test Facility to Support 500 kWe Engine Development

- **Unique Features**
  - Custom liner designed to capture lithium plume when cooled. Liner can be heated to melt and drain lithium metal.
  - 1 MWt cooling capability
  - 9000 A discharge current capability
- **Applications**
  - Performance testing 500 kWe-class lithium MPD thrusters
  - Characterization of high power lithium thruster plumes

Vacuum chamber liner is designed to safely handle lithium propellant